The Origin of Helicity in the Solar Active Regions

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Abstract

We present calculations of helicity based on our solar dynamo model and show that the results are consistent with observational data.

1 Introduction

It is known that solar active regions usually have some helicity associated with them. Several authors established this from magnetogram studies of active regions (Seehafer 1990; Pevtsov, Canfield & Metcalf 1995; Abramenko, Wang & Yurchishin 1997; Bao & Zhang 1998; Pevtsov, Canfield & Latushko 2001). There are different ways of describing helicity mathematically, one of which is

$$\alpha = \frac{(\nabla \times \mathbf{B})_z}{B_z},\tag{1}$$

where z corresponds to the vertical direction. Since $\nabla \times \mathbf{B}$ will be non-zero only if the magnetic field has a helical structure, α is a good measure of helicity. Fig. 1 presents observational data showing values of α for active regions which emerged at different latitudes. It is clear that there is a preference for negative helicity in the northern hemisphere and positive helicity in the southern hemisphere. The preference is at about 70% level.

2 Basic idea

Our theoretical calculations are based on the solar dynamo model developed by Nandy & Choudhuri (2002) and Chatterjee, Nandy & Choudhuri (2004). Here we touch upon the bare essentials of the model. The toroidal field is produced within the high-latitude tachocline, where helioseismology has discovered strong shear. Then the toroidal field is advected by the meridional circulation to lower latitudes where it enters the convection zone and becomes buoyant. Magnetic buoyancy makes the toroidal flux tubes rise to the solar surface where the poloidal field is generated by the Babcock–Leighton mechanism, i.e. from the decay of tilted bipolar regions.

Dynamo models deal with mean fields, whereas we want to find helicities of active regions which form from flux tubes. To make a connection between these two, we have to look at the relation between dynamo
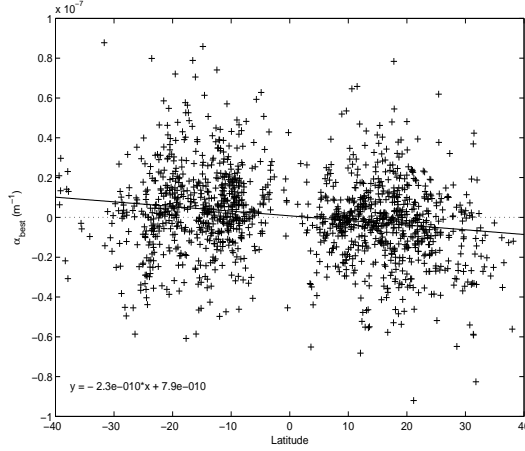
Figure 1: Helicity α for active regions at different latitudes. Based on data for the duration 1985–2002.

theory and flux tubes. This has been explored by Choudhuri (2003), who presents the qualitative idea of how the helicity is generated. Fig. 2 shows a section of the convection zone *in the northern hemisphere*, with the pole towards left and the equator towards right. Suppose the flux tubes at the bottom have magnetic field into the paper. Keeping in mind that the leading sunspot is found near the equator, it is easy to see that the rising flux tubes will produce a clockwise poloidal field by the Babcock–Leighton mechanism. Now consider a flux tube rising in this region of existing poloidal field. Since the magnetic field is nearly frozen, the flux tube will drag the poloidal field lines which get wrapped around the tube in anti-clockwise sense. This implies a current out of the paper, whereas the magnetic field inside the tube is into the paper—giving a negative helicity.

To estimate the magnitude of helicity, keep in mind that the flux of poloidal field B_P through the whole convection zone gets dragged by the rising flux tube. If d is the depth of the convection zone, the flux dragged by the tube is

$$F \approx B_P d. \tag{2}$$

If this flux F gets wrapped around the tube of radius a, then the magnetic field around the tube is of order F/a. The current $|\nabla \times \mathbf{B}|$ associated with this field is of order F/a^2 and is along the axis of the tube. If B_T is the magnetic field inside the flux tube, then it follows from (1):

$$\alpha \approx \frac{F/a^2}{B_T} \approx \frac{B_P d}{B_T a^2} \tag{3}$$

on substituting from (2) for F. On using $B_P \approx 1$ G, the field inside sunspots $B_T \approx 3000$ G and the radius of the sunspot $a \approx 2000$ km, we get $\alpha \approx 0.2 \times 10^{-7}$ m^{-1}. Thus, from very simple arguments, we get the correct order of magnitude.

3   Results from simulation

For simplicity, let us assume that all flux tubes have the same radius a. It then follows from (3) that the helicity of the flux tube is essentially given by the flux F through the convection zone. Hence, whenever an eruption takes place in our dynamo simulation, we calculate the poloidal flux through the convection
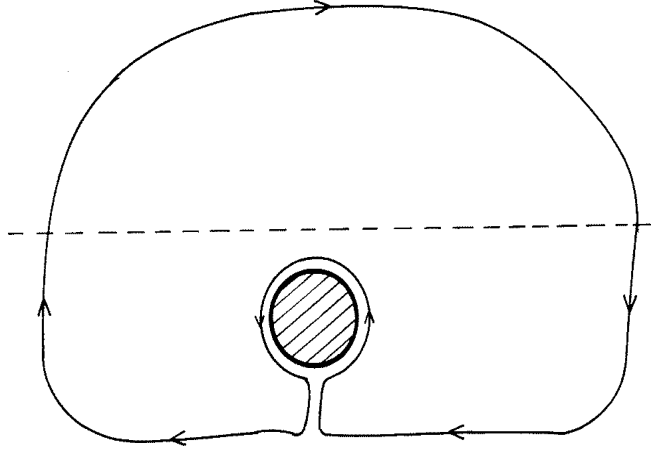
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Figure 2: Magnetic field lines around a rising flux tube, with the dashed line indicating the solar surface. The flux tube shown by the shaded circle has toroidal field going into the paper, and is rising through a region of clockwise poloidal field lines.

zone by integrating B_θ in the radial direction at that latitude. This gives the helicity associated with the eruption.

Fig. 3 shows the simulated butterfly diagram, indicating where the helicity is positive and where it is negative. During the solar maximum, the helicity is negative in the northern hemisphere and positive in the southern, as we expect. However, at the beginning of a cycle, there is a short duration when the helicity is 'wrong'. Bao, Ai & Zhang (2000) reported the evidence of such 'wrong' helicity at the beginning of Cycle 23. Basically, when a flux tube erupts in a region where the poloidal field has been created by *similar* flux tubes which erupted earlier, we get the correct helicity, as can be seen from Fig. 2. At the beginning of a cycle, however, flux tubes emerge in regions where the poloidal field was produced by flux tubes of the earlier cycle, thereby giving rise to opposite helicity. Finally Fig. 4 is a plot of helicity associated with eruptions at different latitudes. In our dynamo model, so far we have not introduced fluctuations, which is needed to model irregularities of the solar cycle. We are now in the process of introducing fluctuations in our dynamo model, which should increase the scatter in the helicity plot. Even now, Fig. 4 is not a bad theoretical match for the observational Fig. 1.

4   Conclusion

Two clear theoretical predictions follow from our model.

1. Since the helicity goes as a^{-2} as seen from (3), the smaller sunspots should statistically have stronger helicity.

2. At the beginning of a cycle, helicity should be opposite of what is usually observed.

There is an alternative model for the generation of helicity: the Σ-effect proposed by Longcope, Fisher & Pevtsov (1998). This model also makes the prediction (a), but not (b). According to this model, the
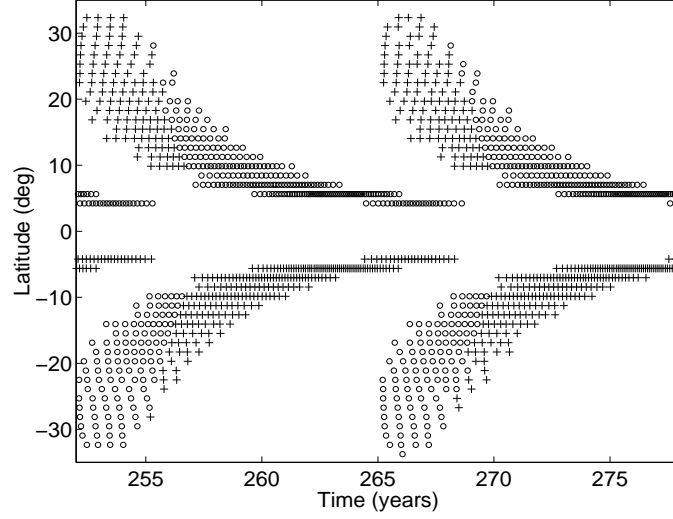
Figure 3: Theoretical butterfly diagram of eruptions from our dynamo simulations. Eruptions with positive and negative helicities are denoted by '+' and 'o' respectively.
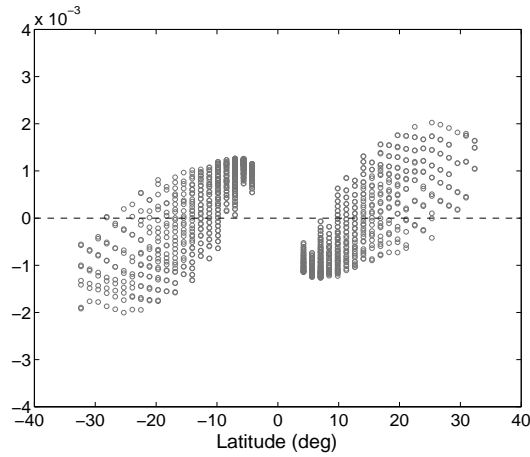

Figure 4: Helicity (in arbitrary units) for eruptions at different latitudes. The hemispheric preference is found to hold for about 67% of the eruptions. Compare this theoretical plot with Fig. 1.

helicity should not vary with the solar cycle. As already noted, Bao, Ai & Zhang (2000) noticed indications of opposite helicity at the beginning of Cycle 23, which lends support to our model. More careful analysis of observational data is needed to establish any possible cycle-dependence of helicity. We hope that this will be done in near future.

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